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CRITICAL SUCCESS FACTORS FOR ENHANCING THE BUILDING INFORMATION MODELLING IMPLEMENTATION IN BUILDING PROJECTS IN SINGAPORE

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Abstract. Although building information modelling (BIM) has been implemented in building projects in Singapore, barriers such as the duplicate efforts for designers and contractors to create models appear to exist. Thus, BIM implementation needs to be enhanced. The objectives are to identify the critical success factors (CSFs) for enhancing BIM implementation and investigate the interrelationships among these CSFs. 32 success factors were identified through a literature review and a questionnaire survey was conducted. The results indicated that 15 CSFs were identified and grouped into integration and accuracy of models (IAM), commitment and training from the management (CTM), and advantages and support of implementation (ASI) through factor analysis. The results from structural equation modelling (SEM) analysis revealed that CTM resulted in IAM and from ASI, while ASI facilitated IAM. The proposed framework indicating the CSFs and the intergroup relationships provides an in-depth understanding of BIM implementation and can help firms to commit on their part of project-wide BIM adoption and associated advantages. Overseas practitioners may use the identified success factors and follow the method to customise their own CSFs.

Keywords: building projects, building information modelling (BIM), critical success factors (CSFs), factor analysis, structural equation modelling (SEM), Singapore.

Introduction

Building information modelling (BIM) implementation has been driven in the global construction industry. Smith (2014) found that one common way for governments to commit on BIM is to encourage, specify, or mandate BIM use in publicly funded construction and building projects. This is consistent with some of the latest studies on the situation and development of the world-wide BIM implementation (Cheng, Lu 2015; Silva *et al.* 2016; McAuley *et al.* 2017). For example, different levels of the public sector in the United States (US) have released BIM standards to effectively implement BIM that is mandated in various states; the third version of the National BIM Standard-US would be released in late 2015, offering a full consensus standard for BIM in the planning, design, construction, and operations of building projects (Cheng, Lu 2015). The United Kingdom (UK) government has required a minimum of Level 2 collaborative BIM on all centrally funded public projects since April 2016 and issued a suite of guidelines to specify the information management in the design, construction, and operations phases (Silva *et al.* 2016; McAuley *et al.* 2017). The large number of large public sector owners in Norway set out particular requirements for all project participants to use open standards for BIM since July 2016, such as the latest Statsbygg BIM manual. Denmark developed Cuneco Classification System (CCS) which provides a common language and methods for creating unambiguous exchange of information throughout the construction process from idea to operation; the standards CCS Identification and CCS Levels of Information were released in 2015 and 2016 (McAuley *et al.* 2017). The buildingSMART Finland published the InfraBIM requirements in 2015, which would be used as general technical references and modelling guidelines, accompanied by the Inframodel 3 data exchange format, during procurement and construction. Supported by the German government and industry, Planen-bauen 4.0 would guide and steer the digital design, construction, operation, and facility management for all types of projects as well as all procurement types and forms of contracts since December 2015, requiring all new projects to implement BIM from 2020 onwards. Other countries such as South Korea, France, and Spain would include BIM implementation in all public sector projects by 2016, 2017, and March 2018, respectively (Cheng, Lu 2015; McAuley *et al.* 2017). Meanwhile, Cheng and Lu (2015) reported that Singapore leads BIM implementation in Asia because many efforts have been made by the local government to achieve the industry-

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wide BIM implementation. For instance, architectural and engineering e-submissions in BIM format have been mandated for all new building projects with a gross floor area over 5,000 m^2 since July 2015, and the Building and Construction Authority (BCA) has been driving the whole construction value chain to work collaboratively for enhancing project-based BIM collaboration, rather than lonely firm-based BIM implementation. Despite the efforts made, changing towards a higher level of BIM implementation is generally slow in most construction practitioners (Porwal, Hewage 2013). One possible reason for this is that these practitioners tend to be entrenched in the traditional project delivery using object-oriented Computer-Aided Design (CAD) (Eastman *et al.* 2011) or adopt a wait-and-see attitude (Juan *et al.* 2017). Besides, there are many challenges for BIM implementation, such as the owners' request in limited phases and subcontractors' poor knowledge and skills to implement BIM (Kiani *et al.* 2015). Thus, BIM implementation still needs to be enhanced in the global construction industry.

To implement BIM successfully, project management teams should identify the critical success factors (CSFs) and thus take measures to ensure the effective implementation of these key areas. However, few research has been conducted to study the holistic view of the success factors for enhancing BIM implementation in the lifecycle of building projects in the Singapore context; for instance, Oo (2014) investigated the CSFs in the local construction industry, but the CSFs were not holistic because it focused on the architectural firms rather than the whole construction value chain. Hence, it is necessary to gain an in-depth understanding of the CSFs in the building project context in Singapore. In this study, success factors are the motivations that drive all key participants in a building project to change from the traditional CAD approach to implement BIM collaboratively from the early design stage to the facility management stage; such factors require high level attention and management priority to be really implemented (Won *et al.* 2013). The objectives of this study are to: (1) identify the CSFs for enhancing BIM implementation in building projects in Singapore, and (2) investigate the interrelationships among these CSFs.

The managerial implications drawn from this study may help the construction practitioners to tailor strategies to implement the CSFs for enhancing their BIM implementation. By identifying the CSFs, the teams may better predict the probability of successful BIM implementation and the necessary steps to avoid failure. Although this study focuses on BIM implementation in the Singapore construction industry, the construction practitioners in other countries can prepare their customised lists of CSFs and better understand the key areas that are worth paying attention to for enhancing BIM implementation according to their unique situations, with the help of the success factors identified in this study. Besides, the method adopted in this study can be used by overseas practitioners. Thus, it is believed that this study significantly contributes to the global body of knowledge related to BIM implementation.

1. Literature review

Previous studies have reported that many factors would affect the successful BIM implementation in building projects. For example, studies of the SmartMarket Report series (Young *et al.* 2008, 2009; Bernstein *et al.* 2010, 2012; Lee *et al.* 2012) may be the most comprehensive survey studies in the US, European, and Korean markets, but concentrated on identifying the barriers to BIM implementation rather than success factors. Gu and London (2010) identified the factors for selecting appropriate BIM software applications in a company and for exchanging data using the applications. Jung and Joo (2011) considered factors such as property, relation, standards, and construction business function when setting up a BIM framework. Nevertheless, these studies failed to consider other factors such as the contractual relationships among the participating firms in the project. Other studies (Gilligan, Kunz 2007; Yan, Damian 2008) were also limited in the identification of success factors. Without an holistic view of the success factors, firms may find it difficult to implement BIM collaboratively (Eastman *et al.* 2011). For example, Lam (2014) reported that the design consultancy firms in Singapore had implemented BIM, but 80% of BIM implementation in the local construction industry was firm-based, rather than project-wide collaboration. The duplicate efforts for the designers and the contractors to create building information models respectively are common both in Singapore (Lam 2014) and overseas (Sattineni, Mead 2013).

In this study, a total of 32 success factors have been identified from 30 previous studies, as listed in Table 1 which also shows the number of the success factors studied by each reference. These studies usually investigated only a few specific factors that enhanced BIM implementation in particular countries rather than studying all the 32 success factors comprehensively. Among the references that involved 10 or more success factors, Gao and Fischer (2006) and Kunz and Fischer (2012) focused on driving contractors and designers to work collaboratively on design models so that construction issues can be identified and solved virtually before actual construction commences, but the involvement of owners and facility managers was limited in this process. Eastman *et al.* (2011) studied the most success factors to enhance BIM implementation but did not identify the key role of government agencies in terms of their active involvement in the design process to specify BIM use as well as their financial support such as subsidising training and consultancy costs. Khosrowshahi and Arayici (2012) proposed a roadmap for implementing BIM in the UK construction industry but did not drive off-site prefabrication which facilities BIM use. Won *et al.* (2013) investigated the CSFs that were commonly considered to enhance BIM

Table 1. Success factors to enhance BIM implementation

Code	Success factors	References																													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
SF01	BIM vision and leadership from the management		√		√													√					√			√				√	√
SF02	Changes in organisational structure and culture			√	√	√												√				√				√				√	
SF03	Stakeholders seeing the value of adopting their own part of BIM			√	√																√	√	√			√				√	
SF04	Training on new skillsets and new ways of working			√	√	√					√		√					√				√				√	√			√	√
SF05	Owner's requirement and leadership to adopt BIM	√		√		√							√																	√	
SF06	Regulatory agencies' early participation to BIM use	√									√															√					
SF07	Gaining competitive advantages from full BIM use			√									√					√													
SF08	All disciplines sharing models in a "Big Room"										√	√				√	√			√	√		√		√	√				√	
SF09	Government support such as subsidising training, software, and consultancy costs										√							√				√				√					√
SF10	Enabling subcontractors to use lower-skilled labour on site								√											√							√				
SF11	OSM lowering safety risks by controlling work in factory								√	√							√								√				√		
SF12	Alignment of the interests of all stakeholders																		√											√	
SF13	Governance of BIM-related policies and standards				√						√							√								√					√
SF14	Data sharing and access on BIM platforms				√						√							√								√				√	
SF15	Three-dimensional (3D) visualisation enabling design communication		√										√		√	√		√		√	√		√					√			
SF16	Four-dimensional simulation before construction	√											√		√	√					√		√	√	√						
SF17	Design coordination between disciplines through clash detection and resolution	√	√				√					√	√		√	√		√		√	√		√	√	√	√		√		√	
SF18	Complex design analysis in sustainability, material selection, and constructability	√							√				√			√	√				√		√			√	√				
SF19	Project lifecycle costing						√									√					√				√						
SF20	Producing models and drawings for construction and fabrication	√					√					√	√			√		√					√			√					
SF21	High accuracy of model-based documentation												√			√					√										
SF22	More off-site fabrication and assembly of standard elements							√	√					√	√	√				√			√		√		√				
SF23	Automatic model updating and drawing production to deal with design changes and their implications											√				√					√										
SF24	Lifecycle information management improving facility management		√					√			√				√	√					√							√			
SF25	Increasing use of design-build and fast-track approach												√																	√	

Continued Table 1

Code	Success factors	References																													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
SF26	On-site work proceeds in parallel with off-site production								√	√							√								√						
SF27	OSM standardises design and manufacturing processes, simplifying construction and testing and commissioning processes								√	√															√		√		√		
SF28	OSM enabling better quality and consistency of building elements								√	√															√						
SF29	OSM reduces building wastes, especially on-site wastes							√	√	√															√						
SF30	Integrating model management tools with enterprise systems to share data				√																										
SF31	Increasing complexity in buildings, project delivery, and marketplace					√							√					√												√	
SF32	New technologies such as Computer Numerically Controlled machines										√	√	√										√		√						
Total number of success factors studied		6	4	5	7	4	3	3	8	5	8	5	12	1	5	11	4	11	1	5	10	4	10	2	11	12	5	3	2	11	4

Note: (1) American Institute of Architects, California Council (AIACC 2014); (2) Aranda-Mena *et al.* (2009); (3) Arayici *et al.* (2011); (4) Autodesk (2012); (5) Azhar *et al.* (2014); (6) BCA (2013); (7) Bernstein and Pittman (2004); (8) Blismas and Wakefield (2009); (9) Blismas *et al.* (2006); (10) Cheng and Lu (2015); (11) Chua and Yeoh (2015); (12) Eastman *et al.* (2011); (13) Fischer *et al.* (2014); (14) Fischer (2008); (15) Gao and Fischer (2006); (16) Gibb and Isack (2003); (17) Juan *et al.* (2017); (18) Kent and Becerik-Gerber (2010); (19) Khanzode *et al.* (2007); (20) Khosrowshahi and Arayici (2012); (21) Kiani *et al.* (2015); (22) Kunz and Fischer (2012); (23) Li *et al.* (2009); (24) McFarlane and Stehle (2014); (25) Oo (2014); (26) Ross *et al.* (2006); (27) Sattineni and Mead (2013); (28) Selvaraj *et al.* (2009); (29) Won *et al.* (2013); (30) Zahrizan *et al.* (2013).

implementation in a firm, which was different from the present study aiming to identify the CSFs in the project level. Without the consensus of all the major stakeholders in the project to implement BIM collaboratively, the project-wide implementation of BIM cannot be realised based on individual party's efforts. This previous study also lacked the consideration of government aspects and new construction methods such as off-site prefabrication which would facilitate BIM implementation. McFarlane and Stehle (2014) concentrated on incorporating off-site manufacture (OSM) process into BIM implementation. Oo (2014) identified the CSFs for enhancing BIM implementation in the architectural firms in Singapore, but the implementation was also firm-based; meanwhile, this said study failed to identify the CSFs in terms of the new construction methods. Juan *et al.* (2017) studied the factors affecting firms to enhance BIM implementation, which was limited in the architectural firms in Taiwan. Other previous studies investigated even fewer success factors (Table 1). Therefore, none of the previous studies had provided a comprehensive understanding of the 32 success factors. In addition, despite the multitude of research that have studied BIM implementation, few have attempted to investigate the interrelationships among the CSFs. Thus, this study expands the literature related to BIM implementation.

2. Method

The research method is shown in Figure 1. To investigate the significance of the success factors for enhancing BIM implementation, a questionnaire survey was performed. The preliminary questionnaire was developed with support from the literature review and revised based on a pilot study in which interviews were conducted with five BIM experts in Singapore to solicit comments on the readability, accuracy, and comprehensiveness of the questionnaire. All the experts had at least three years' experience of implementing BIM in building projects in Singapore. Three of them were project manager, corporate BIM manager, and technical manager of large construction and development firms with over 10 years' experience in this field; the other two included one quantity surveying in charge from a general construction firm and one senior architectural associate from a large architectural firm, with more than five years' work experience. In the final questionnaire, the research objectives and contact details were presented, followed by the questions to profile respondents. The respondents were then requested to rate the significance of the 32 factors in enhancing the BIM implementation in one of their building projects, using a five-point Likert scale (1 = very insignificant, 2 = insignificant, 3 = neutral, 4 = significant, and 5 = very significant). The population consisted of all the construction industry practitioners in Singapore. The sampling frame comprised the BCA, the Urban Redevelopment Authority, the Housing and Development Board (HDB), the private building developers registered with the Real Estate Developers' Association of Singapore, the architectural consultancy firms registered with the Singapore Institute of Architects, the structural and mechanical, electrical, and plumbing (MEP) consultancy firms registered with the Association of Consulting Engineers Singapore, the contractors registered with the BCA, and the facility management firms registered with the Association of Property and Facility Managers. Among the contractors, only larger ones were approached as they are likely to have more resources needed for implementing BIM; meanwhile, a number of contractors with multiple BCA financial grades were calculated according to the highest tendering limit, rather than being calculated repeatedly. Thus, a list of 659 firms was obtained for this survey.

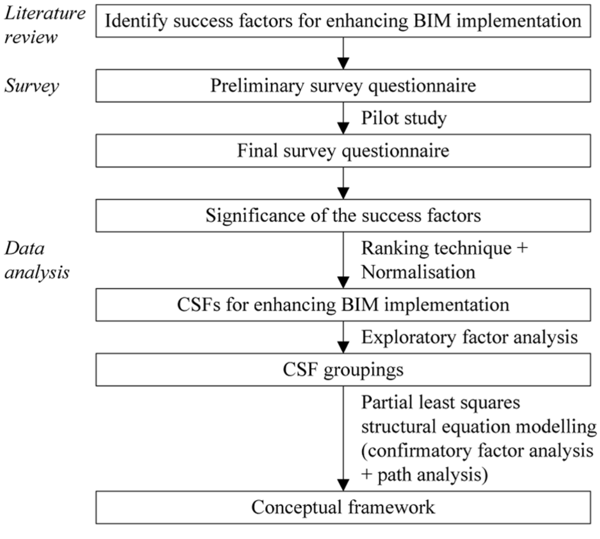

Fig. 1. Research method

3. Survey results and data analysis

3.1. Respondents' profile

A total of 58 completed questionnaires were received, yielding a response rate of 8.80%. The profile of the respondents is presented in Table 2. 53.45% of the respondents had over 10 years' experience in the construction industry. In terms of respondent organisation, apart from the main businesses listed in Table 2, the remainder (17.24%) included government agencies (3.45%), the HDB (1.72%), private developers (5.17%), and other types of consultancy firms (6.90%). Regarding financial grades, 43.10% of the organisations were registered contractors, while the rest were mainly government agencies, developers, consultancy firms, and a facility management firm, indicating a balanced distribution of the service providers. In addition, over half (58.62%) of the organisations had less than three years' experience in implementing BIM in their building projects because the mandatory BIM implementation started in July 2015. The mandate was accompanied by a new BIM fund to grow the collaboration capabilities of the practitioners beyond just modelling within their own firms, which would defray part of the initial costs in training, consultancy,

Table 2. Profile of respondents and their organisations

Profile	Frequency	Percentage (%)
Respondent		
Discipline		
Government agent	2	3.45
Developer	4	6.90
Architect	13	22.41
Structural designer	6	10.34
MEP designer	7	12.07
General contractor	19	32.76
Subcontractor	3	5.17
Supplier/Manufacturer	1	1.72
Facility manager	3	5.17
Years of experience		
5–10	27	46.55
11–15	6	10.34
16–20	6	10.34
21–25	9	15.52
> 25	10	17.24
Organisation		
Main business		
Architectural firm	12	20.69
Structural engineering firm	6	10.34
MEP engineering firm	10	17.24
General construction firm	18	31.03
Trade construction firm	1	1.72
Facility management firm	1	1.72
Others	10	17.24
BCA financial grade		
A1	16	27.59
A2	2	3.45
C1	1	1.72
C3	1	1.72
Single grade	1	1.72
L6	2	3.45
L3	2	3.45
Not applicable	33	56.90
Years of BIM adoption		
0	6	10.34
1–3	28	48.28
4–5	14	24.14
6–10	8	13.79
> 10	2	3.45

software, and hardware (BCA 2016). Because of these government efforts, all the respondents were equipped with experience, knowledge, or skills of implementing BIM in the current or near future projects. Thus, the data were used in the subsequent analysis. This provided clear evidence that the local construction industry had been moving from the traditional project delivery into BIM-based project delivery and was shifting to industry-wide BIM implementation. Thus, although the sample size was not large, it was representative in the Singapore construction industry and the data probably reflected the professional views of key BIM users on the success factors.

3.2. CSFs for enhancing BIM implementation

The Cronbach's alpha coefficient of the 32 success factors was 0.959, which was much higher than the threshold of 0.70 (Robinson *et al.* 1991), indicating high data reliability. These success factors were ranked based on their significance mean scores, ranging from 2.966 to 4.241, as shown in Table 3. The normalised values of the mean scores were calculated. The success factors which obtained mean scores closer to the maximum mean score of all success factors were deemed as CSFs. This method

Table 3. Ranking of the success factors to enhance BIM implementation

Code	Mean	Rank	Normalisation[a]
SF01	4.241	1	1.000
SF02	3.759	12	0.622
SF03	3.793	9	0.649
SF04	4.000	3	0.811
SF05	3.983	4	0.797
SF06	3.897	5	0.730
SF07	3.845	7	0.689
SF08	3.828	8	0.676
SF09	3.862	6	0.703
SF10	2.966	32	0.000
SF11	3.190	27	0.176
SF12	3.500	18	0.419
SF13	3.552	16	0.459
SF14	3.690	13	0.568
SF15	3.793	9	0.649
SF16	3.397	23	0.338
SF17	4.034	2	0.838
SF18	3.552	16	0.459
SF19	3.241	25	0.216
SF20	3.776	11	0.635
SF21	3.638	15	0.527
SF22	3.466	19	0.392
SF23	3.466	19	0.392
SF24	3.328	24	0.284
SF25	3.414	22	0.351
SF26	3.224	26	0.203
SF27	3.138	29	0.135
SF28	3.138	29	0.135
SF29	3.103	31	0.108
SF30	3.690	13	0.568
SF31	3.431	21	0.365
SF32	3.190	27	0.176

Note: [a]Normalised value = (mean − minimum mean)/(maximum mean − minimum mean).

was adopted in previous studies (Xu *et al.* 2010; Zhao *et al.* 2014, 2015), which identified the factors with normalised values equal to or greater than 0.50 as critical ones. This study also adopted this principle. The results showed that 15 out of the 32 success factors received normalised values above 0.50, indicating that these 15 factors were CSFs for enhancing BIM implementation in building projects. Meanwhile, the 15 CSFs received *p*-values below 0.05 in the one-sample *t*-test. In addition, the mean scores of the 15 CSFs were greater than the total mean value (3.566) of all the 58 responses, while the mean score (3.552) of SF13 that was ranked 16th was below the total mean value. Thus, the result was also consistent with the method adopted by Won *et al.* (2013) which set the total mean value as the threshold to select CSFs. Among the CSFs, "BIM vision and leadership from the management" (SF01) ranked top, implying that the management support in the industry players would be the most efficient driving force to implement BIM.

3.3. Underlying CSF groupings

Exploratory factor analysis (EFA) uncovers a relatively small set of common underlying factors that represent the correlations among a large set of interrelated variables. EFA is conducted using a two-step procedure: factor extraction and factor rotation. The former is to identify the initial number of factor groupings underlying the large set of variables, while the latter makes the groupings more interpretable and determines the number of the underlying groupings (Hair *et al.* 2009). Thus, EFA was adopted in this study to explore the underlying groupings among the CSFs. Kaiser-Meyer-Olkin (KMO) test and Bartlett's test of sphericity were performed to measure the degree of intercorrelations among the CSFs and/or the appropriateness of EFA. The KMO value was 0.816, higher than the threshold of 0.60 recommended by Netemeyer *et al.* (2003), suggesting a high degree of common variance among the CSFs. The Bartlett's test of sphericity significance probability was 0.000, indicating that the entire correlation matrix was not an identity matrix and there were relationships among the CSFs (Hair *et al.* 2009). Therefore, the collected data were appropriate for EFA.

As for factor extraction, principal component analysis (PCA) was used to identify the underlying grouped factors because of its distinctive characteristic of data-reduction capacity. Factors with eigenvalues above 1.00 were retained (Hair *et al.* 2009). Factor rotation can be orthogonal or oblique. This study adopted the oblique rotation because it is best suited to obtain several theoretically meaningful factors. Besides, it is often unrealistic to assume the orthogonality of factors because few factors in the real world are uncorrelated and forcing the factors to be orthogonal may be biased in practice (Hair *et al.* 2009). In this study, promax rotation method was applied which begins with a varimax solution and then raises factor loadings to a stated power designated kappa. Consequently, small loadings become close to zero, whereas large loadings remain substantial. Extraction with promax rotation was also adopted in previous project management studies using EFA (Zhao *et al.* 2014).

The EFA process is terminated when its requirements have been met, including cumulative percentage of variance (CPV) of all extracted factors, and the communalities and factor loadings of the variables. The CPV should be at least 0.60. The communality of a variable is the percent of the total variance of the variable accounted for by all the extracted factors, with a threshold of 0.50 (Hair *et al.* 2009). The factor loading of a variable represents the correlation coefficient between the variable and the associated extracted factor. Hair *et al.* (2009) noted that the loadings greater than ±0.40 are considered important, and that if the loadings are ±0.50 or greater, they are considered practically significant. The most common cut-off value of the loadings is 0.40 (Peterson 2000). In this study, because the sample size (58) was smaller than five times of the number of the CSFs, the cut-off value of the loadings needs to be increased (Hair *et al.* 2009). However, Hair *et al.* (2009) also stated that a smaller loading is needed due to the large number of variables to be analysed, and the measure of sampling adequacy value using KMO was high (0.839). Thus, this study increased the cut-off value of the factor loadings to 0.45 (Comrey 1973).

PCA with promax rotation was conducted in three rounds in accordance with the thresholds. SF09 with a very low communality (0.274) and a low factor loading (0.233) as well as SF08 (factor loading at 0.409) were deleted stepwise in the second and the third rounds. Table 4 presents the EFA results that a factor structure for the remaining 13 variables was very well defined, representing three distinct groups of CSFs. The three CSF groupings were interpreted as "integration and accuracy of models" (Grouping 1), "commitment and training from the management" (Grouping 2), and "advantages and support of implementation" (Grouping 3). In addition, the CPV explained from the three groupings was 68.347%, indicating that the three extracted groupings could explain 68.347% of the total information (variance) of the 13 CSFs, higher than the threshold of 60% for a robust EFA. In addition, all factor loadings of the 13 CSFs were above 0.45 (Table 4). It should be noted that the deletion of the two problematic CSFs were considered reasonable and would not harm the achievement of the research objectives because of the reasons: (1) the groupings of the remaining 13 CSFs were consistent in the three rounds of EFA; (2) the problematic CSFs, if included, would be poorly represented and interpreted by the factor structure and harm the ability of the structure to represent and interpret the remaining CSFs. Specifically, the factor loadings or communality of SF09 and SF08 were below the adjusted cut-off value (0.45) recommended by Comrey (1973) and Hair *et al.* (2009); and (3) the inclusion of the problematic CSFs in the factor structure would result in inaccurate relationships and interaction mechanisms

Table 4. Results of the EFA on CSFs to enhance BIM implementation

CSF code	CSF for enhancing BIM implementation	Communality	CSF grouping		
			1	2	3
Grouping 1: integration and accuracy of models (IAM)					
SF20	Producing models and drawings for construction and fabrication	0.754	0.902	–	–
SF30	Integrating model management tools with enterprise systems to share data	0.684	0.841	–	–
SF21	High accuracy of model-based documentation	0.730	0.774	–	–
SF14	Data sharing and access on BIM platforms	0.747	0.763	–	–
Grouping 2: commitment and training from the management (CTM)					
SF01	BIM vision and leadership from the management	0.550	–	0.845	–
SF02	Changes in organisational structure and culture	0.736	–	0.835	–
SF04	Training on new skillsets and new ways of working	0.688	–	0.778	–
SF03	Stakeholders seeing the value of adopting their own part of BIM	0.641	–	0.693	–
SF05	Owner's requirement and leadership to BIM adoption	0.702	–	0.481	–
Grouping 3: advantages and support of implementation (ASI)					
SF15	3D visualisation enabling design communication	0.708	–	–	0.904
SF06	Regulatory agencies' early participation to BIM use	0.759	–	–	0.743
SF17	Design coordination between disciplines through clash detection and resolution	0.613	–	–	0.703
SF07	Gaining competitive advantages from full BIM use	0.573	–	–	0.494
Eigenvalue		–	6.169	1.555	1.161
Variance (%)		–	47.452	11.961	8.934
CPV (%)		–	47.452	59.413	68.347

among the three CSF groupings in subsequent structural equation modelling (SEM) analysis. Instead, such deletions would make the EFA and the SEM analysis more robust.

3.4. Interrelationships among CSF groupings

Based on the EFA results, a conceptual framework was developed to describe the CSFs and the hypothetical relationships among the three CSF groupings (Fig. 2). This framework involves three hypotheses:

- *Hypothesis 1*: the commitment and training from the management positively influences the integration and accuracy of models;
- *Hypothesis 2*: the advantages and support of implementation positively influence the commitment and training from the management; and
- *Hypothesis 3*: the advantages and support of implementation positively influence the integration and accuracy of models.

SEM has been considered as one of the most suitable statistical methods to test and estimate the relationships among multiple variables (Zhao *et al.* 2013, 2014; Xue *et al.* 2015). SEM involves two types of variables: observed variables and latent variables. The former can be directly measured from a survey or some type of observation, whereas the latter is constructed from the observable variables. A SEM model consists of measurement models and a structural model. In this study, the measurement models specify the relationships between each CSF (the observed variable) and its associated grouping (the latent variable), while the structural model provides the dependence relationships linking the three groupings (the latent variables). Furthermore, there are two types

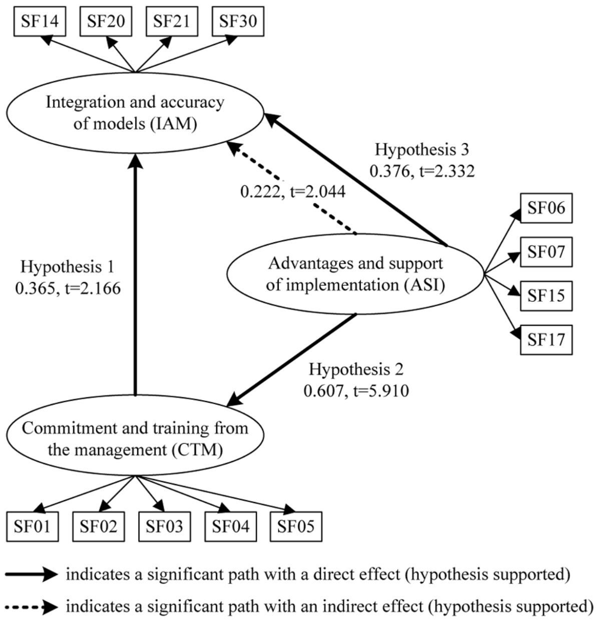

Fig. 2. Conceptual framework for enhancing BIM implementation

Table 5. CFA measurement model evaluation

Grouping	CSF code	Factor loading	*t*-value	AVE	Cronbach's Alpha	CR
IAM	SF14	0.888	19.961	0.737	0.881	0.918
	SF20	0.849	15.897			
	SF21	0.884	28.869			
	SF30	0.812	10.501			
CTM	SF01	0.582	3.280	0.626	0.849	0.892
	SF02	0.815	10.578			
	SF03	0.832	11.152			
	SF04	0.848	15.123			
	SF05	0.846	21.414			
ASI	SF06	0.784	10.168	0.594	0.773	0.853
	SF07	0.821	13.458			
	SF15	0.664	3.615			
	SF17	0.804	10.019			

Note: IAM = integration and accuracy of models; CTM = commitment and training from the management; ASI = advantages and support of implementation.

of SEM: covariance-based SEM (CB-SEM) and partial least squares structural equation modelling (PLS-SEM). Researchers (Hair *et al.* 2012a, 2012b) found that PLS-SEM has certain advantages over CB-SEM in terms of data requirement. For example, PLS-SEM has a minimal sample size requirement because it does not require the normal distribution of data. Thus, PLS-SEM has been widely adopted in previous studies on project management (Doloi 2014; Ning 2014; Zhao *et al.* 2014). This study adopted PLS-SEM because of the inadequate sample size for CB-SEM, and the primary goal of exploring the intergroup relationships or identifying the key driving constructs (Hair *et al.* 2011). On the other hand, the ratio of sample size (58) to the maximum number (5) of paths aiming at any construct in the measurement and structural models in this study was 11.60, higher than the criterion of 10.00 for robust PLS-SEM estimations recommended by Barclay *et al.* (1995).

SEM maximally fits the data and a structural model because of simultaneously conducting both confirmatory factor analysis (CFA) and path analysis in a single SEM model (Lim *et al.* 2011). CFA can test how well the observed variables (measurement items) represent their associated latent variables. In this study, the CSF groupings resulted from EFA were regarded as the latent variables in the structural and measurement models. CFA was conducted to explore the fit between the data and the measurement models, and thus to confirm that the 13 CSFs presented well the CSF groupings derived from the EFA results. This approach was recommended by Thompson (2004) and Zhao *et al.* (2014).

The reliability and validity of the measurement models should be assessed using the following indicators: (1) the Cronbach's alpha coefficient should be at least 0.70 for adequate internal consistency (Hair *et al.* 2009); (2) the factor loadings of observed variables should be 0.55 or higher for good interpretation, and ideally 0.71 or higher (Tabachnick, Fidell 2007); (3) the average variance extracted (AVE) of the observed variables should be at least 0.50 or greater to imply adequate convergent validity (Hair *et al.* 2009); and (4) the composite reliability (CR) score should be at least 0.70 (Hair *et al.* 2011). In addition, the discriminant validity that describes the extent to which a latent construct is truly distinct from the other constructs should also be evaluated. Specifically, the square root of the AVE of each latent construct should be greater than the correlation between this construct and any other constructs; a measurement item's loading on its associated grouping should exceed its cross loadings (Fornell, Larcker 1981; Hair *et al.* 2011).

CFA was carried out using the SmartPLS 3.2.6. The results are shown in Tables 5–7. Table 5 indicated that all the factor loadings were above 0.55 with significance at 0.05 level (critical *t*-value = 1.96), and that the Cronbach's alpha, AVE, and CR values were all greater than their corresponding thresholds. Table 6 suggested that no correlation between any two CSF groupings was higher than the square root of their AVE values. Table 7 implied that all the CSFs had the highest loading on their associated groupings. These provided clear evidence that the three CSF groupings were consistent internally and dis-

Table 6. Discriminant validity of latent constructs

Grouping	IAM	CTM	ASI
IAM	0.859[a]	–	–
CTM	0.594	0.791[a]	–
ASI	0.598	0.607	0.771[a]

Note: IAM = integration and accuracy of models;
CTM = commitment and training from the management;
ASI = advantages and support of implementation.
[a]Square root of AVE of each grouping.

Table 7. Cross loadings for individual observed variables

Observed variable	IAM	CTM	ASI
SF14	0.888	0.597	0.523
SF20	0.849	0.466	0.467
SF21	0.884	0.518	0.578
SF30	0.812	0.443	0.478
SF01	0.220	0.582	0.302
SF02	0.490	0.815	0.436
SF03	0.509	0.832	0.458
SF04	0.475	0.848	0.483
SF05	0.562	0.846	0.644
SF06	0.328	0.573	0.784
SF07	0.574	0.522	0.821
SF15	0.413	0.271	0.664
SF17	0.508	0.465	0.804

Note: IAM = integration and accuracy of models;
CTM = commitment and training from the management;
ASI = advantages and support of implementation.

tinctive. Therefore, the measurement models were reliable and valid for the structural path modelling.

Furthermore, bootstrapping method (Davison, Hinkley 1997) was adopted to test the statistical significance of the path coefficients in the structural model and thus test the hypotheses. A large number of bootstrap subsamples should be used, such as 5,000 (Hair *et al.* 2011) which was applied in this study. The subsamples were randomly drawn from the 58 responses. The two-tailed critical *t*-value was 1.96 at the 0.05 significance level. Table 8 presents the results and indicates that all the path coefficients (direct effects) for the three hypotheses were positive and significant. Thus, these hypotheses were supported. In addition to the ASI's direct effect on the IAM, its indirect effect via the CTM was also positively supported at the 0.05 level.

In addition to the global criterion of assessing the path coefficients and their significance, more evidence for or against the PLS-SEM model's quality would be useful as supplementary analysis since PLS-SEM does not allow assessment of model fit as CB-SEM does (Hair *et al.* 2012b), except for standardised root mean residual (SRMR). The SRMR of the PLS-SEM results was 0.093, not exceeding the threshold of 0.10 (Hair *et al.* 2009). In addition, since PLS-SEM and CB-SEM are complementary rather than competitive (Hair *et al.* 2012b), CB-SEM was also conducted. The results showed that the CMIN/DF value was 1.251, below the threshold of 3.00, with the *p*-value (0.088) significant at the 0.05 level, and that the root mean square error of approximation was 0.066, lower than the suggested cut-off value of 0.08 (Hair *et al.* 2009). Furthermore, the hypotheses were also validated through using the PLS-SEM and randomly setting aside three responses. All the survey responses were coded in chronological order. A list of three numbers (27, 35, 53) was randomly generated from the random numbers table. The data of the remaining 55 responses were analysed using the SmartPLS 3.2.6. The results indicated that all the factor loadings, Cronbach's alpha, AVE, and CR values regarding the measurement model were also higher than their thresholds, and that the path coefficients (*t*-values) for hypotheses 1–3 were 0.360 (2.108), 0.603 (5.893), and 0.380 (2.348), respectively. The indirect effect of the ASI on the IAM was 0.217 (1.981). Compared with the results in Table 8, these figures were only slightly changed. Therefore, it could be concluded that the results in this study were stable. Hence, the SEM model in this study fitted the data well and thus the conceptual framework in Figure 2 was validated. The rationale behind this framework is discussed in the subsequent section.

4. Discussions

In this study, 15 CSFs to enhance BIM implementation in building projects were identified and categorised into three groupings. These groupings were confirmed by the PLS-SEM results as all the relevant statistical indicators were acceptable.

CSF Grouping 1, "integration and accuracy of models", consisted of four CSFs, accounting for 47.452% of the total variance. Among the CSFs, "integrating model management tools with enterprise systems to share data" (SF30), "data sharing and access on BIM platforms" (SF14), and "producing models and drawings for construction and fabrication" (SF20) were associated with the integration of digital models that are necessary for the successful BIM implementation among multiple stakeholders. Computer-based integration enables a project team to share data among disparate modelling and analysis applications reliably by using exchange standards such as Industry Foundation Classes (IFC) (Kunz, Fischer 2012). "High accuracy of model-based documentation" (SF21) would promote the integration in order for

Table 8. Evaluation of hypotheses

Hypothetical path	Direct effect		Indirect effect		Total effect		Interpretation
	Value	*t*-value	Value	*t*-value	Value	*t*-value	
CTM → IAM	0.365	2.166	–	–	0.365	2.166	Supported
ASI → CTM	0.607	5.910	–	–	0.607	5.910	Supported
ASI → IAM	0.376	2.332	0.222	2.044	0.598	5.014	Supported

Note: IAM = integration and accuracy of models; CTM = commitment and training from the management;
ASI = advantages and support of implementation.

the downstream firms to document the accurate information from the integrated 3D models. In the design stage, where key stakeholders including contractors physically co-locate in a "Big Room", the structural engineer can use the initial architectural model as a base and adjust, not re-create, the model to create and analyse a structural model, while the MEP engineers can create a MEP model on the same design. The design team can then produce a composite model by linking the structural and MEP models back into the original architectural model (Gao, Fischer 2006; Porwal, Hewage 2013). In addition, based on the models shared from the design team, contractors can document the construction intent, produce construction models and fabrication models, especially for off-site manufacturing, as well as required drawings, and constantly update the models during the construction period till the project is completed and an as-built model is created.

CSF Grouping 2, "commitment and training from the management", comprised five CSFs and represented 11.961% of the total variance. "BIM vision and leadership from the management" (SF01), "changes in organisational structure and culture" (SF02), "stakeholders seeing the value of adopting their own part of BIM" (SF03), and "owner's requirement and leadership to adopt BIM" (SF05) were associated with the commitment from the management that is critical because top-down approaches are very important both in the project and in individual organisations (Autodesk 2012). Therefore, the owner' requirement on its service providers to implement BIM and the service providers' insights into the value of implementing their part of BIM are essential (Arayici *et al.* 2011; Azhar *et al.* 2014). If the architects, engineers, contractors, fabricators, and the many other related practitioners don't see the value in committing on their part of BIM processes, BIM implementation in this project will likely be stunted (Khosrowshahi, Arayici 2012; Kunz, Fischer 2012; Kiani *et al.* 2015). In addition, such top-down approaches must be accompanied by bottom-up approaches such as training the staff to carry out specific work processes to truly reap the advantages of BIM implementation (Autodesk 2012). Specifically, "changes in organisational structure and culture" (SF02) and the other CSF under this grouping, "training on new skillsets and new ways of working" (SF04), are associated with the mindset, skills, and experience of the staff. Indeed, it is challenging to change the way that the staff carry out various activities, such as entrenching themselves in the traditional CAD approach due to their poor BIM skills or psychological resistance to change. Thus, only the senior-level support such as arranging training programmes on new knowledge and skillsets can enable changes to the existing culture and work practices (Arayici *et al.* 2011; Azhar *et al.* 2014; Zhao *et al.* 2014; Kiani *et al.* 2015). The project and organisational context could be changed first, leading to changed attitudes and associated behaviours.

CSF Grouping 3, "advantages and support of implementation", consisted of four CSFs and accounted for 8.934%. Among the CSFs, "gaining competitive advantages from full BIM use" (SF07) was associated with corporate competitive advantage over those without successful BIM implementation, whereas "3D visualisation enabling design communication" (SF15) and "design coordination between disciplines through clash detection and resolution" (SF17) were related to model-based advantages over two-dimensional (2D) drafting practices. Firms with successful experience of implementing BIM would gain a competitive advantage in meeting project requirements and win bids in future projects, which ensures the long-term viability of the firms and drives them to enhance the capability of implementing their part of BIM in return. In addition, the functions of 3D models, such as visualisation, rendering, coordination, and walkthrough, enable the project team to communicate the design intent more clearly and effectively with each other, and with the owner. In particular, many owners prefer 3D models and cannot understand clearly complex 2D shop drawings because they are not trained architects. Besides, the visualisation and simulation also facilitate the coordination across the design models from different disciplines. Similar findings were also reported by previous studies (Sattineni, Mead 2013; Fischer *et al.* 2014; Wong *et al.* 2014). With the help of these functions, the construction impact can be easily studied when any change occurs in the later stages, enabling the team to select the optimal design option. Furthermore, the other CSF under this grouping, "regulatory agencies' early participation to BIM use" (SF06), was related to government support to implement BIM. This early involvement can minimise agency comments and required changes to the design as submitted for permit. In Singapore, part of the initial costs in training, consultancy, software, and hardware will be subsidised (BCA 2016).

Hypothesis 1, that the commitment and training from the management (Grouping 2) positively influences the integration and accuracy of models (Grouping 1), was supported by the PLS-SEM results. Although all key stakeholders team together, they remain responsible for individual scopes of work and associated deliverables. The collaboration between designers and contractors does not inherently result in the integration between disciplines. If not all key stakeholders commit on their work processes using BIM, discipline-specific models cannot be shared and integrated collaboratively and openly in the project for high accurate documentation of design and construction intent. For instance, it is common today for the design team to produce one model and for contractors to develop their own model based on the information provided to them (Sattineni, Mead 2013). Thus, the owner' requirement in certain contract documents for and the service providers' commitment and training on proper model creation, sharing, and integration are very critical to enhance BIM implementation in the project. Once different participants' models and relevant data are shared and integrated within the team collaboratively, each participant can use them as bases for analysing and creating their own models and accurate drawings appropriately (Gao, Fischer 2006; Porwal, Hewage 2013; Rezgui *et al.* 2013).

Hypothesis 2, that the advantages and support of implementation (Grouping 3) positively influence the commitment and training from the management (Grouping 2), was also supported by the PLS-SEM results, with the highest effect (Table 8). If the service providers cannot recognise the model-based advantages and competitive edge derived from implementing their own part of BIM in the whole process, they would not commit on the new way of delivering this project. This finding is consistent with a previous study (Khosrowshahi, Arayici 2012) which advocated that it is essential to get the project stakeholders, especially their top management, to understand the advantages of BIM-based work processes over the 2D drafting practices. Nonetheless, committing on BIM requires many resources, such as costly infrastructure and skilled personnel either by training the employees or engaging experts in the market, which are big challenges for many firms, especially small and medium-sized enterprises (Kiani *et al.* 2015). Therefore, the advantage of obtaining long-term competitive edge due to successful BIM implementation and the support of government subsidies can be meaningful for industry players to remove psychological resistance to change and embark on BIM implementation.

Hypothesis 3, that the advantages and support of implementation (Grouping 3) positively influence the integration and accuracy of models (Grouping 1), was supported by the PLS-SEM results, with both direct effect and indirect effect (Table 8). One possible explanation for the direct effect is that the model-based advantages, future viability, and local government support, get the project participants to recognise the project delivery with increasing work processes using BIM. In addition, accurate 3D models are convenient to project participants to communicate design intent and they can share and integrate information from discipline-specific models using IFC (SF14 and SF30). For example, model-based advantages such as visualisation and coordination allow the team to select the optimal design option by showing how close the design comes to the expected outcomes and allowing them to see the consequence of their decisions (Fischer *et al.* 2014). A fully coordinated design model (SF17) enables multiple disciplines to document the construction intent (SF21) and create construction models (SF20) as needed. In terms of the indirect effect, given that both hypotheses 1 and 2 have been justified, it is logical that the advantages and support of implementation can influence the commitment and training from the management whereby the integration and accuracy of models is influenced. In other words, the management of any industry practitioners recognising the advantages and the government support of BIM will likely commit on BIM, allocate resources to train the staff, and require its staff to change their traditional working practices and embrace the BIM-based work processes, such as creating and sharing their own models for the project-wide integration of models. Thus, this participant then fulfils its part of BIM in a collaborative team.

Previous studies (Zahrizan *et al.* 2013; McAuley *et al.* 2017) argued that the successful application of BIM (CSF Grouping 1) would probably influence the advantages and government support of BIM implementation (CSF Grouping 3). In order to test this argument, this study changed the path direction of hypothesis 3 and deleted CSF Grouping 2 in the SEM model, otherwise the three influence paths would become a loop of the same direction which is meaningless in mathematics. The results revealed significant influence of the integration and accuracy of models (Grouping 1) on the advantages and support of BIM implementation (0.612, with *p*-value at 0.000). It is worth reiteration that 3D visualization (SF15) and design coordination (SF17) in Grouping 3 describe the inherent functions of the digital models, while the four CSFs in Grouping 1 represent the successful applications by the major stakeholders in the project. Hence, the significant influence of Grouping 1 on Grouping 3 was considered reasonable, because the inherent model functions (SF15 and SF17) would drive the major stakeholders to apply BIM successfully. In turn, the successful BIM application (Grouping 1) would give the competitive advantage (SF07) to the major stakeholders as well as motivate the local government to provide further leadership and support (SF06) to implement BIM (Grouping 3) in future projects, compared to the traditional CAD approach or the lonely BIM implementation of individual firms.

Conclusions and recommendations

This study has identified the CSFs for enhancing BIM implementation in the Singapore construction industry and investigated the interrelationships among these CSFs. The data was collected using a questionnaire survey and analysed using EFA and PLS-SEM. The results implied that 15 out of the 32 success factors identified from the literature review were CSFs, among which "BIM vision and leadership from the management" (SF01) was recognised as the top CSF. The EFA results suggested that the CSFs were categorised into three underlying groupings: integration and accuracy of models, commitment and training from the management, and advantages and support of implementation. Besides, the path modelling results indicated that the commitment and training from the management contributes to the integration and accuracy of models and is greatly attributed to the advantages and support of implementation, and that the advantages and support of implementation lead to the integration and accuracy of models both directly and indirectly. Thus, the three CSF groupings and their inherent interrelationships constituted a conceptual framework that described the key areas of enhancing BIM implementation. Given the resource constraints, the management of both the project team and each project participant would allocate resources for the most important areas rather than all the key areas.

The overall ranking of the mean scores of the CSFs as well as the relationships among the three CSFs groupings indicated that the vision and leadership from the management (SF01) and the four CSFs in Grouping 3 are key and initial driving forces that should have top management priority. Among these, SF01 and SF07 (pursuit for competitive advantage) is controllable in the project management team; whereas government's leadership and support (SF06) can only be controlled by the local government. This substantiated the argument of Juan *et al.* (2017) that the willingness to implement BIM was mostly influenced by government policies, competitor motivation, and financial incentives and technological support. Certain managerial implications can be drawn from the results for more successful BIM implementation. Firstly, construction practitioners should recognise the model-based advantages over 2D drafting practices such as 3D visualisation and multi-disciplinary coordination as well as the competitive advantage of enhanced BIM implementation in their projects. BIM implementation is a long-term journey spanning many years; those firms that have successfully implemented BIM in the building projects will gain a competitive edge that can help them win bids in the future market. Secondly, project teams should have a visible and continual commitment on enhancing BIM implementation. Owners should recognise the advantages that successful BIM implementation can add to their projects, and commit on driving BIM implementation such as setting relevant contractual requirements when building the project teams. The management of service providers should also have the visible and constant commitment to enhance BIM implementation which, otherwise, will probably be stunted if they cannot see the advantages in implementing their part of BIM (Autodesk 2012). Since the advantages of successful BIM implementation are realised on the shop floor, it will be difficult for their staff to carry out specific work processes without the tone at the top of the hierarchy (Zhao *et al.* 2014). Thirdly, the governments that are still adopting a wait-and-see attitude should have the clear understanding that without their leadership, encouragement, mandates, and support, the local industry may still be stuck to the traditional way in the changing market (Silva *et al.* 2016). Finally, the culture of sharing data and integrating accurate models to create discipline-specific models as needed among the project participants should be cultivated once they team together and carry out BIM-based work processes (Verdecho *et al.* 2012; Rezgui *et al.* 2013). A critical way of cultivating such culture is for the top management both from the owners and the service providers to arrange project-wide or organisation-wide training and education programmes for their staff on new skillsets and new working practices and procedures. This can help remove the resistance of the whole project team to change from entrenching on the traditional working approach to more integrated and collaborative approach.

While this study has achieved the research objectives, there are limitations to the conclusions. Firstly, the response rate was not high. In terms of EFA, the ratio of sample size (58) to the number (13) of variables was 4.46, lower than the requirement (5.00) for a robust analysis. However, it should be noted that this was not a critical issue since this study increased the cut-off value of the factor loadings (Hair *et al.* 2009) and the KMO value (0.839) was adequate for a robust EFA. Secondly, the problematic CSFs were deleted in the EFA and PLS-SEM analysis according to the adjusted threshold for the factor loadings. One may consider including such CSFs in the research context of large sample size. However, the deletion would in turn ensure the ability of the factor structure to represent and interpret the CSFs, which resulted in more accurate relationships and influence paths among the CSF groupings and thus more meaningful findings and contributions in this study. Thirdly, one should be cautious when interpreting and generalising the analysis results in this study since the data were collected from the BIM practitioners with knowledge and/or experience in the Singapore construction industry.

Nevertheless, the managerial implications drawn from this study are not limited to the project teams in Singapore because of the reasons: (1) many governments that have yet made much efforts in driving BIM implementation can refer to the managerial implications drawn from this study to efficiently provide their support on purpose, such as mandating BIM implementation in particular types of building projects, establishing the national data exchange standards between major stakeholders for enhancing project-wide collaboration, subsidizing a certain part of initial costs in training, consultancy, and software subscription, and promoting successful cases of BIM implementation; (2) the construction practitioners in other countries may also use the identified success factors and follow the research method adopted in this study to prepare their own lists of CSFs for enhancing BIM implementation, according to the actual circumstances of their project context and political environment; and (3) this study is novel because it is the first one to investigate the interrelationships of the CSF groupings in building projects. Thus, the results are of considerable importance to the body of knowledge related to BIM implementation globally.

In order to provide more evidence for the PLS-SEM analysis results, future research may attempt to collect qualitative data on the CSFs and CSF groupings identified in this study, which would be analysed to further validate the significant path coefficients among the CSF groupings. Meanwhile, implementing the CSFs to enhance BIM implementation requires project management teams to tailor clear plans. Thus, future work is also needed to identify specific actionable change activities to enhance BIM implementation. In addition, the influence paths of the CSFs will be studied via SEM to demonstrate how these CSFs influence the change activities in building projects.

Disclosure statement

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